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A dust outbreak episode in sub-Sahel West Africa

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Abstract. Wind blown dust is a major contributor to the tropospheric aerosol mass loading and has a significant effect on the local radiative forcing. Information on aerosol optical properties and their temporal and spatial distribution is very limited. Attempts to derive such information from space, in particular, over land, are in a preliminary stage. Recently, information on aerosol optical properties is becoming available from ground networks within one day from the time the observations are made. In this study, use was made of such "real-time" aerosol observations, to characterize their optical properties, during a heavy dust event in the sub-Sahel in January 2000. Aerosol optical depths at all wavelengths showed a sharp increase when compared to the average for the season, reaching values up to 3.5 at 500 nm. The Angstrom exponent was reduced from 1.2 to 0.3, and a sharp increase in the single-scattering albedo was found. The aerosol optical properties differed significantly from climatologically available information on dust aerosols, and therefore their timely assimilation into transport models or weather prediction models could be of great relevance. Developments in the ways aerosol are presently observed could influence future treatment of aerosols in climate research.

1. Introduction

There is a need to obtain information on aerosol properties on global scale, in particular, in areas affected by dust outbreaks and biomass burning. Aerosols have a direct effect on the transfer of radiation in the atmosphere, referred to as "aerosol forcing" [*International Panel on Climate Change (IPCC)*, 1996; *Kaufman and Fraser*, 1997; *Herman et al.*, 1997; *Haywood et al.*, 1999]. Aerosols play a vital role in air quality, have health effects [*Wilson and Spengler*, 1996; *Prospero*, 1999], and can form haze, which is of concern to civil aviation [*Eos Transactions*, 2000]. Attempts are in progress to derive aerosol properties from space [*Griggs*, 1975; *Fraser*, 1976; *Durkee et al.*, 1986; *Kaufman*, 1987; *Tanre and Legrand*, 1991; *Holben et al.*, 1998; *King et al.*, 1992; *Stowe et al.*, 1992; *Deschamps et al.*, 1994; *Herman and Celarier*, 1997; *Mishchenko and Travis*, 1997; *Nakajima and Higurashi*, 1997]. Ground observations of aerosol properties are being used to evaluate the various inference schemes.

Sahara is a major dust source region that affects local and remote areas. *D'Almeida* [1987] suggested the following classification of dust types: background aerosol (fair weather and horizontal visibility higher than 8 km), wind-carried aerosol (conditions following a 1–2 days old heavy dust storm with visibility between 7 and 2 km), and dust storm aerosol (conditions during heavy dust storm with visibility lower than 2 km). The transport of Saharan dust over the Atlantic Ocean as far as the eastern shores of the United States has been known for a long time and investigated extensively [*Carlson and Prospero*, 1972; *d'Almeida*, 1986; *Westphal et al.*, 1987, 1988; *Moulin et al.*, 1997; *Karyampudi et al.*, 1999]. Detailed analyses and numerical simulations of the Saharan air layer and its effect on easterly wave disturbances were reported on by *Karyampudi and Carlson* [1988], and *Westphal et al.* [1988] reported on a case study of mobilization and transport of Saharan dust. The above studies focused on summertime dust outbreaks. Recent studies show that because of consistent droughts since the 1970s [*Faizon et al.*, 1994; *Nicholson*, 2000], the Sahel is also a major source of dust, as well as a source of aerosols from biomass burning.

In the present study, as part of an Earth Observing System (EOS) validation effort, observations were made in a climatically important region in the sub-Sahel, in a transition zone between the Sahara desert and the Guinea savannah zone, which is under the influence of the annual alternating southward and northward passages of the Intertropical Convergence Zone (ITCZ).

Successive outbreaks of extremely dusty air with high turbidity and strong attenuation of solar radiation are observed over this location during the harmattan season (November–February), when biomass burning is also practiced. In this paper we focus on a heavy dust event, which occurred in the last week of January 2000. The peak of the dust event occurred on January 30, 2000, and was characterized by unusual haze and poor visibility conditions. It was of such intensity that flights at the Lagos Airport, Nigeria, were canceled. Accurate monitoring of direct Sun and diffuse sky measurements, using a state-of-the art sky radiometer, is conducted at the observing site. Coupled with the on-line data archive and distribution of these observations by the Aerosol Robotic Network (AERONET) [*Holben et al.*, 1998], it is possible to detect such dust outbreaks as they occur. In this paper, the day-to-day variations in aerosol optical depth, particle size distribution, radiative characteristics, as well as the characterization of the large-scale flow pattern during this event will be presented.

2. Experimental Site

The site is located on the campus of the University of Ilorin, Ilorin, Nigeria (08° 19′ N, 04° 20′ E, 350 m above mean sea

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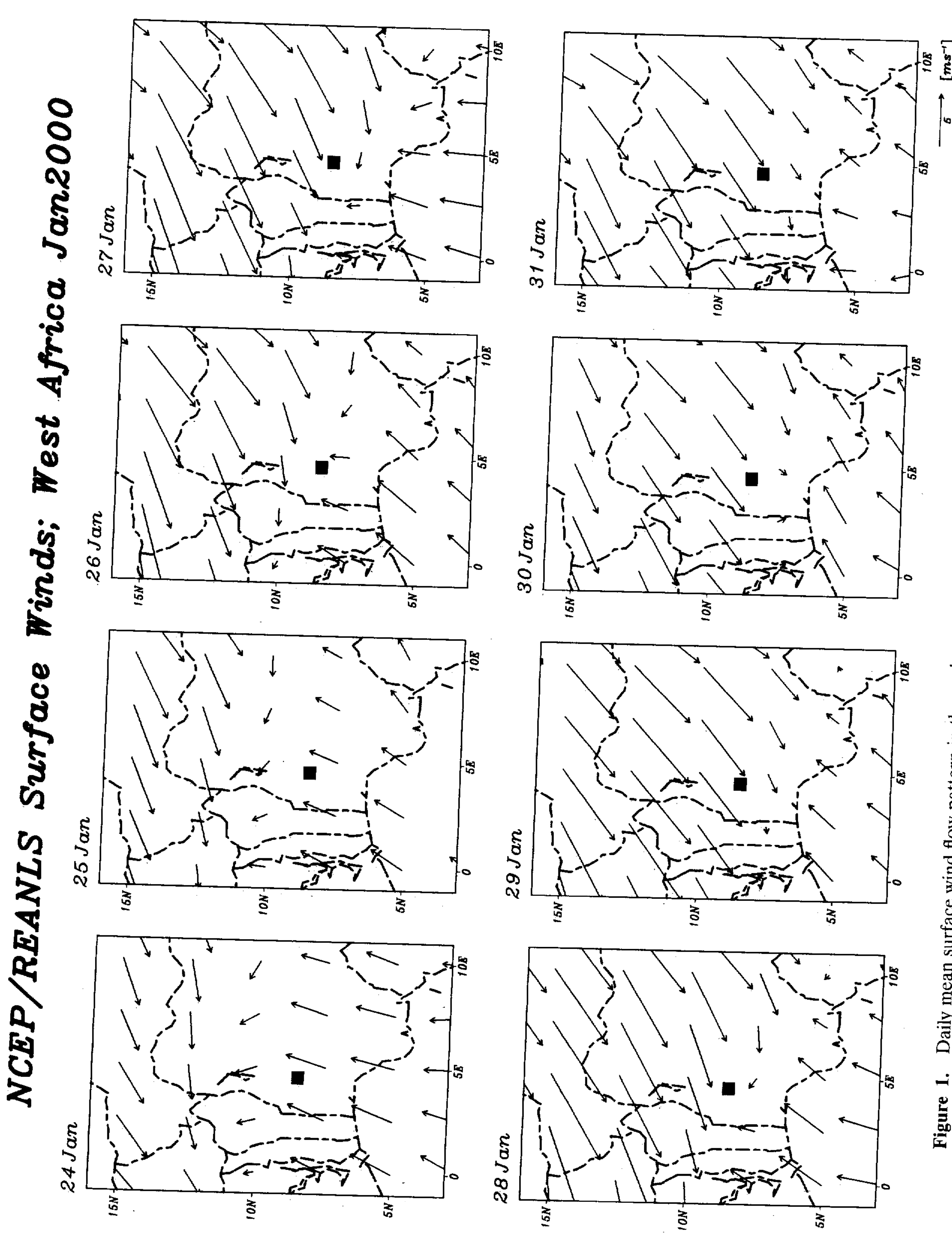

Figure 1. Daily mean surface wind flow pattern in the region surrounding the observing site, both before and during the dust event (January 24–31, 2000).

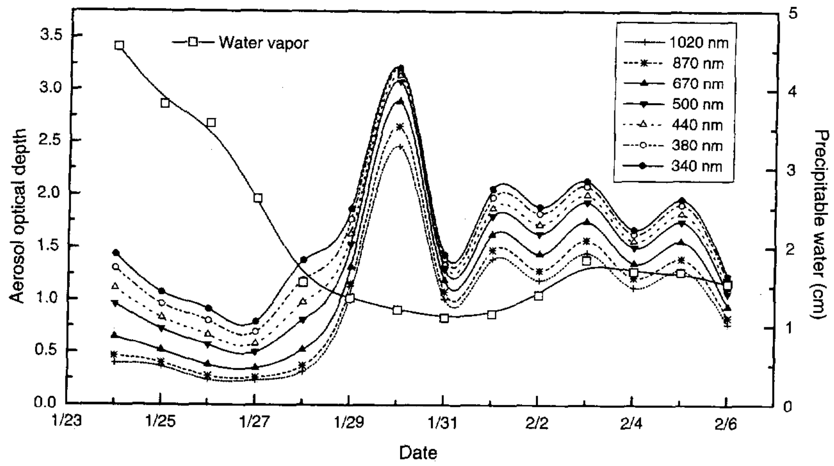

Figure 2. Aerosol optical depth at seven wavelengths, as observed during January 24 to February 6, 2000, at Ilorin, Nigeria.

level (amsl)), at the upper tip of the Guinea savannah zone in the sub-Sahel, under the influence of annual oscillation of the ITCZ (Intertropical Convergence Zone). During the "dry season" (November–February) the prevailing northeasterly wind, known as the "harmattan," brings in air containing Saharan dust from the Chad basin. A large amount of dust particles are transported downwind from the source region in a plume, mainly at the 900 and 850 mbar levels, north of the ITCZ, taking a southwesterly trajectory over Nigeria [*Kalu*, 1979]. During this season, dust plumes can have a thickness of up to 3 km, vary strongly in aerosol content, and reduce the visibility to less than 1 km. Harmattan winds are the main mechanism for dust transport and produce severe winter weather conditions in West Africa, known as the "harmattan haze." Measurements of aerosol optical depths at this site started in 1987 [*Pinker et al.*, 1994], and measurements of surface radiative fluxes started in 1992 [*Miskolczi et al.*, 1997] and were upgraded in May 1995 under the NASA Earth Observing System (Eos) Validation Program. It is aimed to upgrade the observations at this site, to meet the requirements of the World Climate Research Programme (WCRP) Baseline Surface Radiation Measurement (BSRN) Network [*Ohmura et al.*, 1998]. The observations made at the site are stored at the World Radiation Data Center located at the Eidgenossische Technische Hochschule (ETH), Zurich, Switzerland. Observations of aerosol optical properties at Ilorin, Nigeria, were upgraded in May 1998, as part of the Aerosol Robotic Network (AERONET) activity, in support of current and future satellite missions such as the Clouds and the Earth's Radiant Energy System (CERES) and the Moderate Resolution Imaging Spectroradiometer (MODIS).

3. Instrument and Measurements

The instrument used in the present study to monitor aerosol properties is a CIMEL sky radiometer, of the type used in the Aerosol Robotic Network (AERONET), which is a federated network led by the NASA Goddard Space Flight Center [*Holben et al.*, 1998]. This is a worldwide network operated at numerous climatically important regions. The instrument is an automatic Sun-tracking sky radiometer, with a 1.2° field of view and two detectors, to measure direct Sun, aureole, and sky radiances at eight spectral channels. The instrument that is located at Ilorin has filters centered at wavelengths 340, 380,

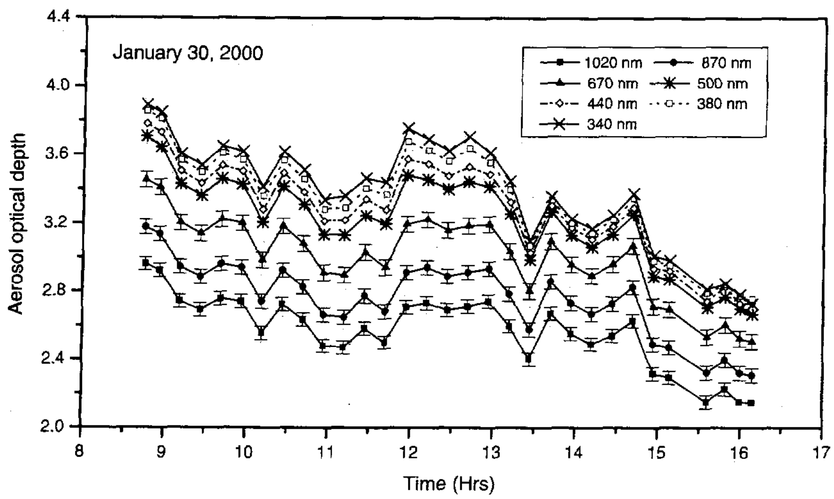

Figure 3. Diurnal variation of aerosol optical depth at seven wavelengths as observed on January 24, 2000, at Ilorin, Nigeria. The error bars indicate standard deviations from the daily mean.

440, 500, 670, 870, 940, and 1020 nm located in a filter wheel that is driven by a stepper motor. One set of measurements requires about 10 s, and measurements are taken in triplets at 30 s intervals. These triplets are used for detecting clouds, based on the assumption that cloud variations within such a short time interval are larger than corresponding variations in aerosol optical depth [*Smirnov et al.*, 2000]. The observations are transmitted close to real time via the European Meteosat (D. Tanre, private communication, 1998), and received at the Goddard Space Flight Center, Greenbelt, Maryland. Detailed information on measurement protocol, radiometric precision, calibration procedures, and processing methods are described by *Holben et al.* [1998]. The inversion procedure [*Dubovik and King*, 2000] utilizes a combination of observed spectral optical depths and sky radiances, in the full almucantar (with angular coverage of scattering angles up to 100° or more). Precipitable water vapor is retrieved using the 940 nm channel, using the method of *Bruegge et al.* [1992].

4. Results and Discussion

Results will be presented on the aerosol optical depth, day-to-day variations of aerosol size distribution, Angstrom exponent, single-scattering albedo, and precipitable water. The variation of the daily average surface wind flow patterns around the dust event date, as provided by the National Center for Environmental Prediction (NCEP) Numerical Weather Prediction (NWP) model analysis (J. Schemm, private communication, 2000) are presented in Figure 1. On January 29 the winds from the desert region were much stronger than before or after the event. Figure 2 illustrates the variation of the spectral aerosol optical depth (AOD) and precipitable water vapor before and after the heavy dust event of January 30, 2000. On January 30, 2000, the optical depths increased from the background harmattan average value of 0.5 at 500 nm to a value of >3.0 at the same wavelength. The day-to-day variations in the wind field (Figure 1) help to explain the high precipitable water vapor and the low aerosol optical depths observed on January 24–26. During this period there was an influx of moist maritime air mass from the Gulf of Guinea. A gradual increase in aerosol optical depths and decrease in precipitable water from January 27 onward was mainly due to the dry continental air mass from the Chad basin and the Sahara. In Figure 3 the variation of aerosol optical depth for January 30 is presented. As evident, there is little variability in the observations, indicating that the episode lasted at least as long as that day's observational period. Spectral dependence of AOD contains information about the size of the particles [*Junge*, 1955; *Rangarajan*, 1972; *Pandithurai et al.*, 1997; *Remer et al.*, 1998]. The Angstrom exponent α can be obtained by fitting a power law to the aerosol optical depth and wavelength [*Eck et al.*, 1999; *Reid et al.*, 1999], as given in the following expression:

$$\tau_a(\lambda) \propto \lambda^{-\alpha}.$$

Daily mean Angstrom exponents computed by fitting the power law to the spectral AODs (Figure 4) show a dramatic change on January 30, 2000, from about 1.2 to 0.3, indicating a strong contribution to extinction from large dust particles. Global distributions of Angstrom exponent retrieved from two-channel radiances [*Nakajima and Higurashi*, 1998; *Mishchenko et al.*, 1999] also reveal small values of α in areas of prevailing soil-derived particles, such as the ocean area close to the Sahara desert.

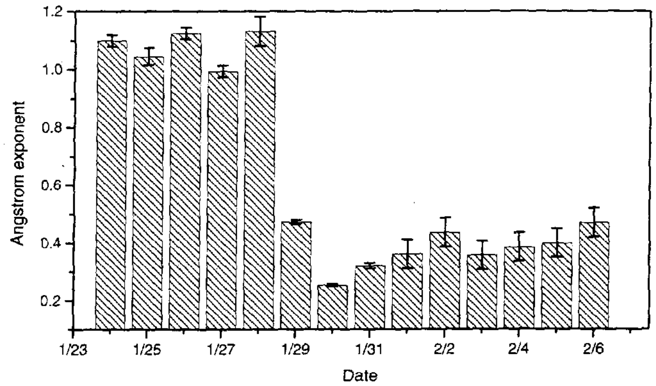

Figure 4. Day-to-day variation of the Angstrom exponent during January 24 to February 6, 2000, at Ilorin, Nigeria.

The day-to-day variations of aerosol size distributions for selected days during the dust outbreak event are grouped into two sets. One group represents days when biomass burning was dominant, while the other, represents days when dust was dominant (Figure 5). Daily mean size distributions during the period when biomass burning prevailed are presented in Figure 5a. The observed size distributions are bimodal (accumulation mode ~0.16 μm; coarse mode ~4 μm) and can be represented as

$$\frac{dV}{d\ln r} = \frac{V_0}{\sigma(2\pi)^{1/2}} \exp\left(-\frac{[\ln (r/r_m)]^2}{2\sigma^2}\right),$$

where $dV/d\ln r$ is the volume distribution, V_0 is the column volume of the particles per cross section of atmospheric column, r is the radius, r_m is the modal radius, and σ is the standard deviation of the natural logarithm of the radii. On

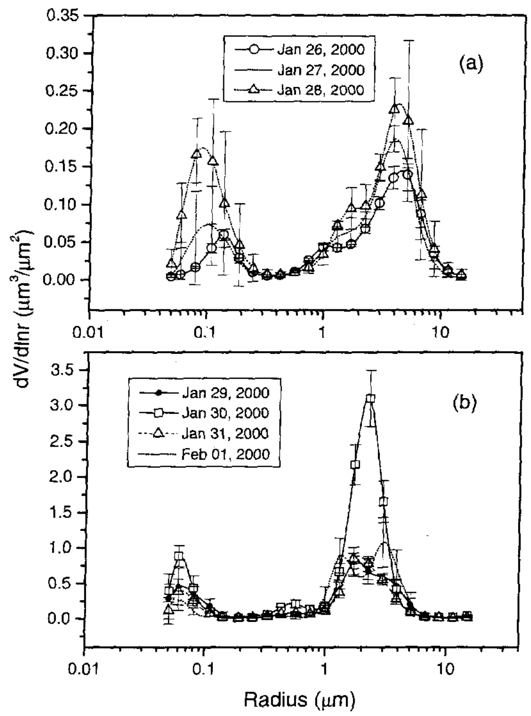

Figure 5. (a)Day-to-day variation of aerosol size distribution during January 26–28; (b) as above during January 29 to February 1, 2000, at Ilorin, Nigeria.

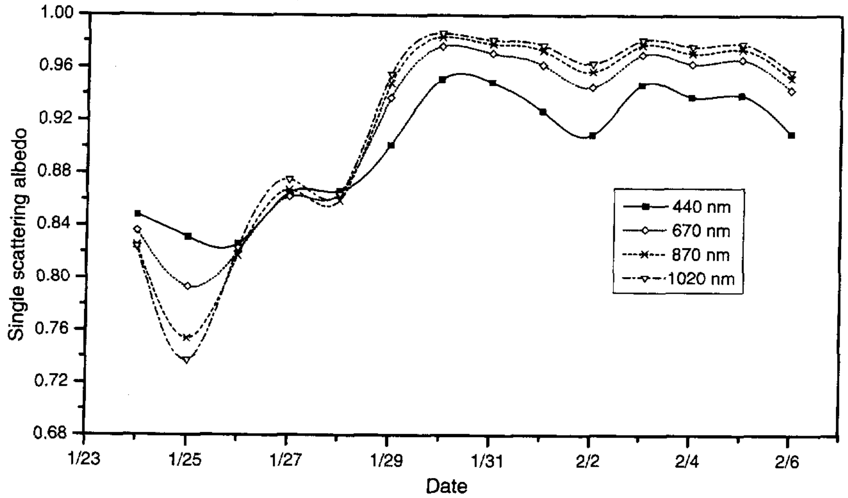

Figure 6. Day-to-day variation of aerosol single-scattering albedo during January 23 to February 1, 2000, at Ilorin, Nigeria.

January 28, 2000, there was a sharp increase in fine particles, which is typical for biomass burning (visual records from local staff at University of Ilorin, Nigeria). The wavelength exponent of aerosol optical depth "α" is greater than 1, which is typical for biomass burning aerosols and a sudden drop in α around 0.3 is typical for desert dust aerosols [*Eck et al.*, 1999].

Figure 5b illustrates the daily mean size distributions observed during the dust outbreak of January 29 to February 1, when large amounts of coarse and fine particles were transported to the site. An order of magnitude increase in volume size distribution can be seen. The volume size distribution was retrieved from the direct solar and diffuse sky radiance measurements as discussed by *Dubovik and King* [2000]. Briefly, in the aerosol-scattering model used in the retrieval algorithm, it is assumed that the aerosols are composed of spherical and homogeneous particles, scattering is simulated using Mie formulation, and multiple-scattering effects are also accounted for. In the retrieval procedure the radiative properties of the atmosphere are determined by the particle size distribution of the aerosol in the total atmospheric column and the complex index of refraction. The inversion of measured radiance to particle size and index of refraction by the scattering model is done as a simultaneous search for the best fit of Sun radiance and the angular distribution of sky radiances measured at four wavelengths (0.44, 0.67, 0.87, and 1.02 μm). Assessment of retrieval accuracy of the aerosol optical properties from Sun and sky radiance measurements by this method can be found in the work of *Dubovik et al.* [2000]. The effects of both random measurement errors and possible systematic offsets originating from instrument degradation or calibration uncertainty were tested for several optically distinct aerosol models. For desert aerosols dominated by coarse particles, the following was found:

volume size distribution	$dV(r)/d\ln r$:	for $0.1<r<7$ μm 15–25%
single-scattering albedo	$\omega_0(\lambda)$:	0.03
refractive index (imaginary)	$k(\lambda)$:	50%
refractive index (real)	$n(\lambda)$:	0.05

The single-scattering albedo is an important parameter in studies of aerosol radiative forcing, in particular, when the aerosols are absorbing, such as those generated from biomass burning. The retrieval of single-scattering albedo of aerosols $\omega_0(\lambda)$ requires estimates of both the extinction optical thickness $\tau_{ext}(\lambda)$ and the scattering optical thickness $\tau_{scat}(\lambda)$:

$$\omega_0(\lambda) = \frac{\tau_{scat}(\lambda)}{\tau_{est}(\lambda)}.$$

The methodology for estimating extinction and scattering optical depths and the associated retrieval of single-scattering albedo can be found in the work of *Dubovik and King* [2000]. In Figure 6, the retrieved single scattering albedo is presented for the selected period. On January 30, it was around 0.95 at all wavelengths. The values cited in literature are about 0.94 for desert dust [*Shettle*, 1984]; about 0.76 for wind carried dust; and about 0.88 for background dust [*d'Almeida*, 1987] at 0.7 μm. Smaller values of single scattering albedo at all wavelengths, and a reversal in the wavelength dependence on days prior to the dust storm, are characteristic of aerosols originating from biomass burning [*Dubovik et al.*, 2001]. The spectral dependence of the single-scattering albedo can decrease or increase with wavelength. This can be clearly seen for the case of January 20, 2000, a typical day when biomass burning occurred at the observing site (Figure 7). During the morning hours, before the presence of aerosols from biomass burning, ω_0 increases with increasing wavelength. When biomass burning started (reported at 1300 LT by local observers), the single-scattering albedo values dropped, and the spectral dependence reversed. Thus the wavelength dependence of the single-scattering albedo can be used as an indicator of aerosol type. Information on the magnitude of the single-scattering albedo is important, in particular, over brighter surfaces, due to its influence on the surface reflectance.

During the entire harmattan season, aerosol optical depths tended to be high (around 1); however, during January 30 the average value was 4 times as high as during the period preceding the event. The Angstrom exponent dropped drastically from 1.1 to a value of 0.3, indicating that larger particles were transported to the observing site by the high winds. Similarly,

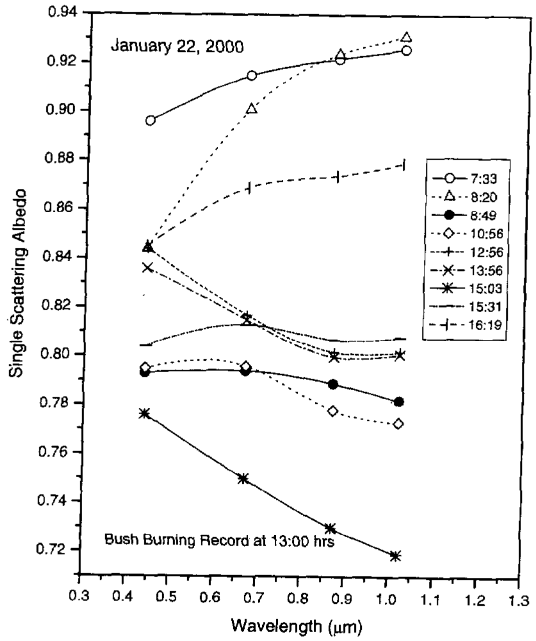

Figure 7. Temporal variation of single-scattering albedo as observed on a typical day when biomass burning was reported in areas surrounding the experimental site.

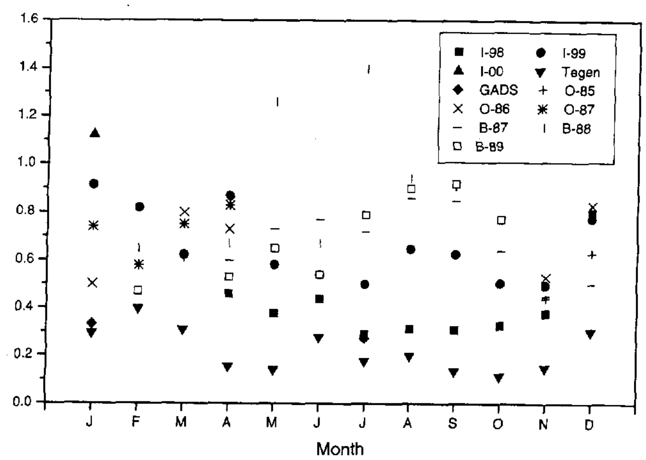

Figure 8. Relevant values of aerosol optical depth for the observing site, as given by *Tegen et al.* [1997]; Global Aerosol Data Sets (GADS) [*Koepke et al.*, 1997], for winter (0% RH) and summer (70% RH), at 500 nm; by *Faizon et al.* [1994], during 1985, 1986, and 1987 over Ouangofitini, Nigeria (O-85, O-86, O-87); by *Faizon et al.* [1994] during January 1987 to September 1989 over Bidi, Nigeria (B-87, B-88, B-89); and monthly mean values at 500 nm as observed over Ilorin, Nigeria, during 1987–1989 and April 1998 to February 2000 (I-87, I-88, I-89, I-98, I-99, I-00).

there was a drastic increase in the volume size distribution, in both the accumulation and the coarse modes, more so in the coarse mode, from a prevent value of 0.75 to 2.5 $\mu m^3/\mu m^2$ (coarse mode). Good agreement was observed between independently derived satellite based aerosol indices (TOMS, AVHRR). TOMS aerosol index [*Torres et al.*, 1998] increased from 0.6 on January 28 to 2.8 on January 30, and the CIMEL-derived AOD at 340 nm increased from 0.97 on January 28 to 3.3 on January 30. A more detailed comparison with such observations and discussion are presented by *Pandithurai et al.* [2000]. In Figure 8 we present a comparison of available estimates of aerosol optical depth for the area of the observational site. These values come from measurements in close proximity, or from transport models, and are frequently used in climate studies. Presented are values from *Tegen et al.* [1997], which are monthly mean totals of nine individual species, derived from transport models, using a grid size of 8° longitude and 4° latitude; values from the Global Aerosol Data Sets (GADS) [*Koepke et al.*, 1997], for winter (0% RH) and summer (70% RH), at 500 nm over a 10°N and 5°E grid box, centered at the ground station; observed values by *Faizon et al.* [1994] during 1985, 1986, and 1987 over Ouangofitini, Nigeria, (O-85, O-86, O-87); observed values by *Faizon et al.* [1994] during January 1987 to September 1989 over Bidi, Nigeria, (B-87, B-88, B-89); and monthly mean values at 500 nm observed over Ilorin, Nigeria, during January and February 1988 (I-88), December 1987 (I-87), February 1989 (I-89), and April 1998 to February 2000 (I-98, I-99, I-00). The underestimation of model values as compared with measurements could be due to the lack of consideration of land-surface processes over Sahel, where drought conditions have persisted since 1970s [*Nicholson*, 2000]. Differences observed within the measurements can be attributed to spatial and temporal variations in aerosol loading. However, the spread between the two types of estimates is quite large. For instance, in January, the peak of the harmattan season, the average observed value is about a factor of 3 larger than the model value. The above average-observed values in May and June 1988 at Bidi, Nigeria, seem to be very high, and there is a possibility of contamination by thin cirrus clouds, which are difficult to detect.

5. Summary

In this paper, observations made during a unique dust event were used in a remote area in sub-Sahel Africa, as available in almost real time. An analysis of the observations revealed that during the dust outbreak event, the optical properties of the dust aerosols were much different than what is known from aerosol climatologies in desert areas, or from observations preceding the dust event. Therefore the ability to incorporate such properties in remote sensing inference schemes, or numerical weather prediction models, is of considerable interest. Several research activities, currently in progress, are leading the way to facilitate such a possibility. The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument currently carried on TERRA, the Earth Observing System (EOS) "flagship" mission, is collecting a global data set of radiances in 36 spectral bands, at a resolution of 0.25–1 km, and similar capabilities will be available on ADEOS-II, scheduled for launch in 2001. The data are well suited for deriving aerosols on a global scale. Global observing networks are in place now (AERONET) to provide ground truth for the satellite-based estimates. At the same time, the need to assimilate such data into weather prediction models has been also recognized [*Alpert et al.*, 1998, 2000]. The ability to use "true" properties of aerosols in such models can help to improve them in a way that until now was not feasible.

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